

# The relativistic continuum Hartree-Bogoliubov description of charge-changing cross section for C, N, O and F isotopes

J. Meng<sup>1-3\*</sup>, S.-G. Zhou<sup>1-3</sup> and I. Tanihata<sup>4</sup>

<sup>1</sup>*Department of Technical Physics, Peking University, Beijing 100871, China*

<sup>2</sup>*Institute of Theoretical Physics, Chinese Academy of Sciences, Beijing 100080, China*

<sup>3</sup>*Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator, Lanzhou 730000, China*

<sup>4</sup>*The Institute of Physical and Chemical Research (RIKEN), Hirosawa 2-1, Wako-shi, Saitama 351-0198, Japan*

(August 1, 2017)

## Abstract

The ground state properties including radii, density distribution and one neutron separation energy for C, N, O and F isotopes up to the neutron drip line are systematically studied by the fully self-consistent microscopic Relativistic Continuum Hartree-Bogoliubov (RCHB) theory. With the proton density distribution thus obtained, the charge-changing cross sections for C, N, O and F isotopes are calculated using the Glauber model. Good agreement with the data has been achieved. The charge changing cross sections change only slightly with the neutron number except for proton-rich nuclei. Similar trends of variations of proton radii and of charge changing cross sections for each isotope chain is observed which implies that the proton density plays

---

\*e-mail: mengj@pku.edu.cn

important role in determining the charge-changing cross sections.

PACS numbers: 21.10.Gv, 21.60.-n, 24.10.Cn, 25.45.De

Key words: Relativistic Continuum Hartree-Bogoliubov (RCHB) theory,  
charge-changing cross section, neutron-rich light nuclei, exotic nuclei

Recent progresses in the accelerator and detection techniques all around the world have made it possible to produce and study the nuclei far away from the stability line — so called “EXOTIC NUCLEI”. Based on the measurement of interaction cross section with radioactive beams at relativistic energy, novel and entirely unexpected features has appeared: e.g., the neutron halo and skin as the rapid increase in the measured interaction cross-sections in the neutron-rich light nuclei [1,2].

Systematic investigation of interaction cross sections for an isotope chain or an isotone chain can provide a good opportunity to study the density distributions over a wide range of isospin [3,4]. However the contribution from proton and neutron are coupled in the measurement of interaction cross section. To draw conclusion on the differences in proton and neutron density distributions definitely, a combined analysis of the interaction cross section and other experiment on either proton or neutron alone are necessary.

The charge-changing cross section which is the cross section for all processes which result in a change of the atomic number for the projectile can provide good opportunity for this purpose. In Ref. [5], the total charge-changing cross section  $\sigma_{cc}$  for the light stable and neutron-rich nuclei at relativistic energy on a carbon target were measured. We will study  $\sigma_{cc}$  theoretically by using the fully self-consistent and microscopic relativistic continuum Hartree-Bogoliubov (RCHB) theory and the Glauber Model in the present letter.

The RCHB theory [6–8], which is an extension of the relativistic mean field (RMF) [9–11] and the Bogoliubov transformation in the coordinate representation, can describe satisfactorily the ground state properties for nuclei both near and far from the  $\beta$ -stability line and from light to heavy or super heavy elements, as well as for the understanding of pseudo-spin symmetry in finite nuclei [12–15]. A remarkable success of the RCHB theory is the self-consistent reproduction of the halo in  $^{11}\text{Li}$  [7] and the prediction of giant halo [8]. In combination with the Glauber model, the RCHB theory successfully reproduces the interaction cross section in Na isotopes [4]. These successes encourage us to apply the RCHB theory to calculate the charge changing cross section of the C, N, O, F isotopes (ranging from the  $\beta$ -stability line to the neutron drip line) on the target of  $^{12}\text{C}$  reported in Ref. [5].

With the density distribution provided by RCHB theory, the total charge-changing cross section can be calculated based on the Glauber model and compared with the data directly [5], as was done in Ref. [4] for the interaction cross section. Since the theory used here is fully microscopic and basically parameter free, we hope it provide us more reliable information on both the proton and neutron distribution.

The ground state properties of C, N, O and F isotopes up to neutron drip line are studied first, including single neutron separation energies, density distributions and radii. Then the total charge-changing cross sections will be calculated from the Glauber model with the density obtained from RCHB calculations.

The basic ansatz of the RMF theory is a Lagrangian density whereby nucleons are described as Dirac particles which interact via the exchange of various mesons (the scalar sigma ( $\sigma$ ), vector omega ( $\omega$ ) and iso-vector vector rho ( $\rho$ )) and the photon. The  $\sigma$  and  $\omega$  meson provide the attractive and repulsive part of the nucleon-nucleon force, respectively. The necessary isospin asymmetry is provided by the  $\rho$  meson. The scalar sigma meson moves in a self-interacting field having cubic and quadratic terms with strengths  $g_2$  and  $g_3$  respectively. The Lagrangian then consists of the free baryon and meson parts and the interaction part with minimal coupling, together with the nucleon mass  $M$  and  $m_\sigma$  ( $g_\sigma$ ),  $m_\omega$  ( $g_\omega$ ), and  $m_\rho$  ( $g_\rho$ ) the masses (coupling constants) of the respective mesons:

$$\begin{aligned} \mathcal{L} = & \bar{\psi}(i\partial - M)\psi + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma) - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} \\ & + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}_\mu\vec{\rho}^\mu - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} \\ & - g_\sigma\bar{\psi}\sigma\psi - g_\omega\bar{\psi}\omega_\mu\gamma^\mu\psi - g_\rho\bar{\psi}\vec{\rho}_\mu\vec{\gamma}\psi - e\bar{\psi}\mathbf{A}\psi \end{aligned} \quad (1)$$

For the proper treatment of the pairing correlations and for correct description of the scattering of Cooper pairs into the continuum in a self-consistent way, one needs to extend the present relativistic mean-field theory to the RCHB [6–8]:

$$\begin{pmatrix} h - \lambda & \Delta \\ -\Delta^* & -h^* + \lambda \end{pmatrix} \begin{pmatrix} U \\ V \end{pmatrix}_k = E_k \begin{pmatrix} U \\ V \end{pmatrix}_k, \quad (2)$$

$E_k$  is the quasi-particle energy, the coefficients  $U_k(r)$  and  $V_k(r)$  are four-dimensional Dirac spinors, and  $h$  is the usual Dirac Hamiltonian

$$h = [\boldsymbol{\alpha} \cdot \mathbf{p} + V(\mathbf{r}) + \beta(M + S(\mathbf{r}))], \quad (3)$$

with the vector and scalar potentials calculated from:

$$\begin{cases} V(\mathbf{r}) = g_\omega \psi(\mathbf{r}) + g_\rho \boldsymbol{\rho}(\mathbf{r}) \boldsymbol{\tau} + \frac{1}{2} e(1 - \tau_3) \mathbf{A} \boldsymbol{\tau}(\mathbf{r}), \\ S(\mathbf{r}) = g_\sigma \sigma(\mathbf{r}). \end{cases} \quad (4)$$

The chemical potential  $\lambda$  is adjusted to the proper particle number. The meson fields are determined as usual in a self-consistent way from the Klein Gordon equations in *no-sea*-approximation.

The pairing potential  $\Delta$  in Eq. (2) is given by

$$\Delta_{ab} = \frac{1}{2} \sum_{cd} V_{abcd}^{pp} \kappa_{cd} \quad (5)$$

It is obtained from the pairing tensor  $\kappa = U^* V^T$  and the one-meson exchange interaction  $V_{abcd}^{pp}$  in the *pp*-channel. As in Ref. [6–8]  $V_{abcd}^{pp}$  in Eq. (5) is the density dependent two-body force of zero range:

$$V(\mathbf{r}_1, \mathbf{r}_2) = \frac{V_0}{2} (1 + P^\sigma) \delta(\mathbf{r}_1 - \mathbf{r}_2) (1 - \rho(r)/\rho_0). \quad (6)$$

The ground state  $|\Psi\rangle$  of the even particle system is defined as the vacuum with respect to the quasi-particle:  $\beta_\nu |\Psi\rangle = 0$ ,  $|\Psi\rangle = \prod_\nu \beta_\nu |-\rangle$ , where  $|-\rangle$  is the bare vacuum. For odd system, the ground state can be correspondingly written as:  $|\Psi\rangle_\mu = \beta_\mu^\dagger \prod_{\nu \neq \mu} \beta_\nu |-\rangle$ , where  $\mu$  is the level which is blocked. The exchange of the quasiparticle creation operator  $\beta_\mu^\dagger$  with the corresponding annihilation operator  $\beta_\mu$  means the replacement of the column  $\mu$  in the  $U$  and  $V$  matrices by the corresponding column in the matrices  $V^*$ ,  $U^*$  [16].

The RCHB equations (2) for zero range pairing forces are a set of four coupled differential equations for the quasi-particle Dirac spinors  $U(r)$  and  $V(r)$ . They are solved by the shooting method in a self-consistent way as [6]. The detailed formalism and numerical techniques of the RCHB theory can be found in Ref. [6] and the references therein. In the present

calculations, we follow the procedures in Ref. [6,8,4] and solve the RCHB equations in a box with the size  $R = 20$  fm and a step size of 0.1 fm. The parameter set NL-SH [17] is used, which aims at describing both the stable and exotic nuclei. The density dependent  $\delta$ -force in the pairing channel with  $\rho_0 = 0.152 \text{ fm}^{-3}$  is used and its strength  $V_0$  is fixed by the Gogny force as in Ref. [6]. The contribution from continua is restricted within a cut-off energy  $E_{cut} \sim 120 \text{ MeV}$ .

Systematic calculations with RCHB theory has been carried out for the C, N, O and F isotopes. The one neutron separation energies  $S_n$  predicted by RCHB and their experimental counterparts [18] for the nuclei  $^{11-22}\text{C}$ ,  $^{13-24}\text{N}$ ,  $^{15-26}\text{O}$  and  $^{17-25}\text{F}$  are given in Fig.1 as open and solid circles respectively. For carbon isotopes, the theoretical one neutron separation energies for  $^{11-18,20,22}\text{C}$  are in agreement with the data. The calculated  $S_n$  is less than 0 (-0.003 MeV) for the odd- $A$  nucleus  $^{19}\text{C}$  which is bound from experiment. While for the experimentally unbound nucleus  $^{21}\text{C}$ , the predicted value of  $S_n$  is positive. From the neutron-deficient side to the neutron drip line, excellent agreement has been achieved for the nitrogen isotopes. Just as the other relativistic mean field approaches, the RCHB calculations overestimate binding for  $^{25,26}\text{O}$  which are unstable in experiment. For fluorine isotopes, the  $S_n$  in  $^{17,26-29}\text{F}$  are overestimated in contrast with the underestimated one in  $^{18}\text{F}$ . The neutron drip line nucleus is predicted as  $^{30}\text{F}$ . In general, the RCHB theory reproduces the  $S_n$  data well considering that this is a microscopic and almost parameter free model. There are some discrepancies between the calculations and the empirical values for some of the studied isotopes. This may be due to deformation effects, which has been neglected here.

The proton density distributions predicted by RCHB for the nuclei  $^{10-22}\text{C}$ ,  $^{12-24}\text{N}$ ,  $^{14-26}\text{O}$  and  $^{16-25}\text{F}$  are given in Fig.2 in logarithm scale. The change in the density distributions for each isotopes chain in Fig.2 occurs only at the tail or in the center part as the proton number is constant. Because the density must be multiplied by a factor  $4\pi r^2$  before the integration in order to give proton number or radii, the large change in the center does not matter very much. What important is the density distribution in the tail part. Compared with the neutron-rich isotopes, the proton distribution with less  $N$  has higher density at the

center, lower density in the middle part (  $2.5 < r < 4.5\text{fm}$  ), a larger tail in the outer part (  $r > 4.5\text{ fm}$  ) which gives rise to the increase of  $r_p$  and  $\sigma_{cc}$  for the proton rich nuclei as will be seen in the following.

The neutron and proton rms radii predicted by RCHB for the nuclei  $^{10-22}\text{C}$ ,  $^{12-24}\text{N}$ ,  $^{14-26}\text{O}$  and  $^{16-25}\text{F}$  are given in Fig.3. The neutron radii for nuclei in each isotope chain increase steadily. While the corresponding proton radii remains almost constant with neutron number for nuclei in each isotope chain except for the proton rich ones.

To compare the charge-changing cross sections  $\sigma_{cc}$  directly with experimental measured values, the densities  $\rho_p(r)$  of the target  $^{12}\text{C}$  and the C, N, O and F isotopes obtained from RCHB ( see Fig.2 ) were used. The cross sections were calculated in Glauber model by using the free nucleon-nucleon cross section [19] for the proton and neutron respectively. The total charge-changing cross sections  $\sigma_{cc}$  of the nuclei  $^{10-22}\text{C}$ ,  $^{12-24}\text{N}$ ,  $^{14-26}\text{O}$  and  $^{16-25}\text{F}$  on a carbon target at relativistic energy are given in Fig. 4. The open circles are the result of RCHB combined with the Glauber Model and the available experimental data [5] are given by solid circles with their error-bars. The agreement between the calculated results and measured ones are fine.

The charge changing cross sections change only slightly with the neutron number except for proton-rich nuclei, which means the proton density plays important role in determining the charge-changing cross sections  $\sigma_{cc}$ . A gradual increase of the cross section has been observed towards the neutron drip line. However, the big error bars of the data can not help to conclude anything here yet. It is shown clearly that the RCHB theory, when combined with the Glauber model, can provide reliable description for not only interaction cross section but also charge changing cross section. From comparison of this figure and Fig.3, we can find similar trends of variations of proton radii and of charge changing cross sections for each isotope chain which implies again that the proton density plays important role in determining the charge-changing cross sections.

Summarizing our investigations, the ground state properties for C, N, O and F isotopes have been systematically studied with a microscopic model — the RCHB theory, where the

pairing and blocking effect have been treated self-consistently. The calculated one neutron separation energies  $S_n$  are in good agreement with the experimental values available with some exceptions due to deformation effects which is not included in the present study. A Glauber model calculation for the total charge-changing cross section has been carried out with the density obtained from the RCHB theory. A good agreement was obtained with the measured cross sections for  $^{12}\text{C}$  as a target. Another important conclusion here is that, contrary to the usual impression, the proton density distribution is less sensitive to the proton and neutron ratio. Instead it is almost unchanged from stability to the neutron drip-line. The influence of the deformation, which is neglected in the present investigation, is also interesting to us, more extensive study by extending the present study to deformed cases are in progress.

This work was partly supported by the Major State Basic Research Development Program Under Contract Number G2000077407 and the National Natural Science Foundation of China under Grant No. 10025522, 19847002 and 19935030.

## REFERENCES

- [1] I. Tanihata, Prog. Part. Nucl. Phys., **35**(1995) 505.
- [2] P.G. Hansen, A.S. Jensen, and B. Jonson, Ann. Rev. Nucl. Part. Sci. **45** (1995) 591
- [3] T. Suzuki, et al., Phys. Rev. Lett. **75** (1995) 3241
- [4] J. Meng, I. Tanihata and S. Yamaji, Phys. Lett. **B419** (1998) 1.
- [5] L.V. Chulkov, et al., Nucl. Phys. **A674** (2000) 330
- [6] J. Meng, Nucl. Phys. **A635** (1998) 3.
- [7] J. Meng, and P. Ring, Phys. Rev. Lett. **77** (1996) 3963.
- [8] J. Meng, and P. Ring, Phys. Rev. Lett. **80** (1998) 460.
- [9] B.D. Serot and J.D. Walecka, Adv. Nucl. Phys. **16**, 1 (1986).
- [10] P-G. Reinhard, Rep. Prog. Phys. **52**, 439 (1989).
- [11] P. Ring, Prog. Part. Nucl. Phys. **37**, 193 (1996).
- [12] J. Meng, K. Sugawara-Tanabe, S. Yamaji, P. Ring and A. Arima, Phys. Rev. C **58** (1998) R628.
- [13] J. Meng, K. Sugawara-Tanabe, S. Yamaji and A. Arima, Phys. Rev. C **59** (1999) 154-163.
- [14] J. Meng, and I. Tanihata, Nucl. Phys. A **650** (1999) 176-196.
- [15] J. Meng, and N. Takigawa, Phys. Rev. C **61** (2000) 064319.
- [16] P. Ring and P. Schuck, *The Nuclear Many-body Problem*, Springer Verlag, Heidelberg (1980)
- [17] M. Sharma, M. Nagarajan and P. Ring, Phys. Lett. **B312** (1993) 377
- [18] G. Audi, and A.H. Wapstra, Nucl. Phys. **A565** (1993) 1

[19] L. Ray, Phys. Rev. **C** 20 ( 1979 ) 1857

FIGURES

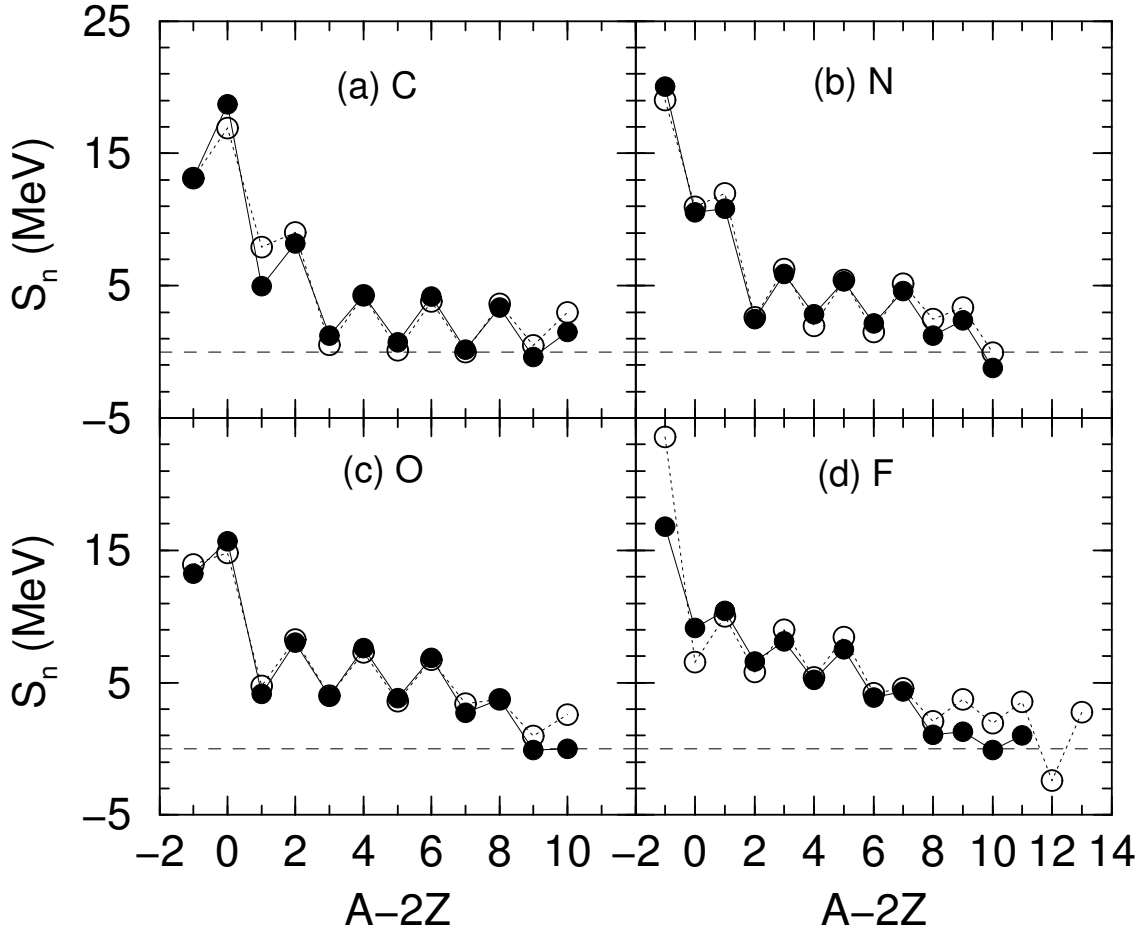


FIG. 1. The one neutron separation energies  $S_n$  for the nuclei  $^{11-22}\text{C}$ ,  $^{13-24}\text{N}$ ,  $^{15-26}\text{O}$  and  $^{17-25}\text{F}$  by RCHB theory (open circles) and their experimental counterparts (solid circles).

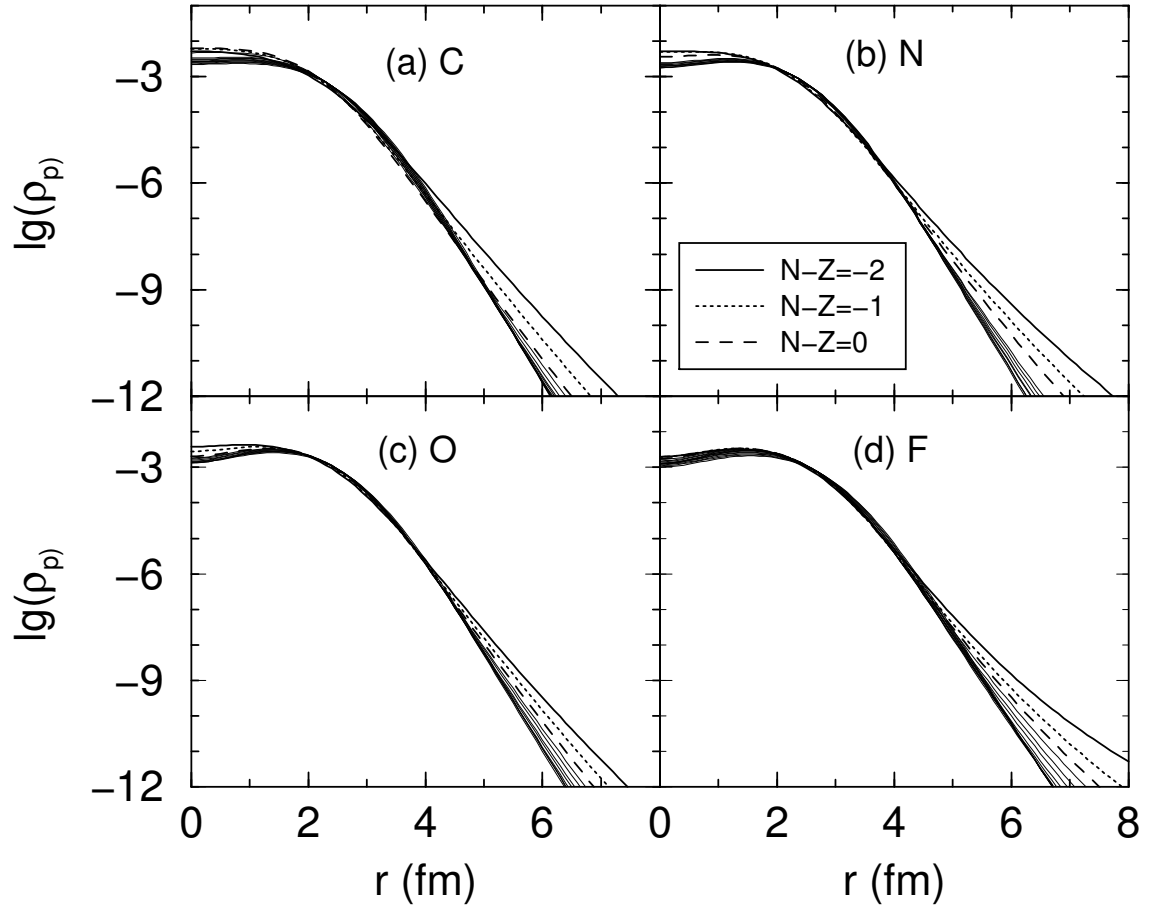


FIG. 2. The proton density distributions predicted by RCHB for the nuclei  $^{10-22}\text{C}$ ,  $^{12-24}\text{N}$ ,  $^{14-26}\text{O}$  and  $^{16-25}\text{F}$  in logarithm scale.

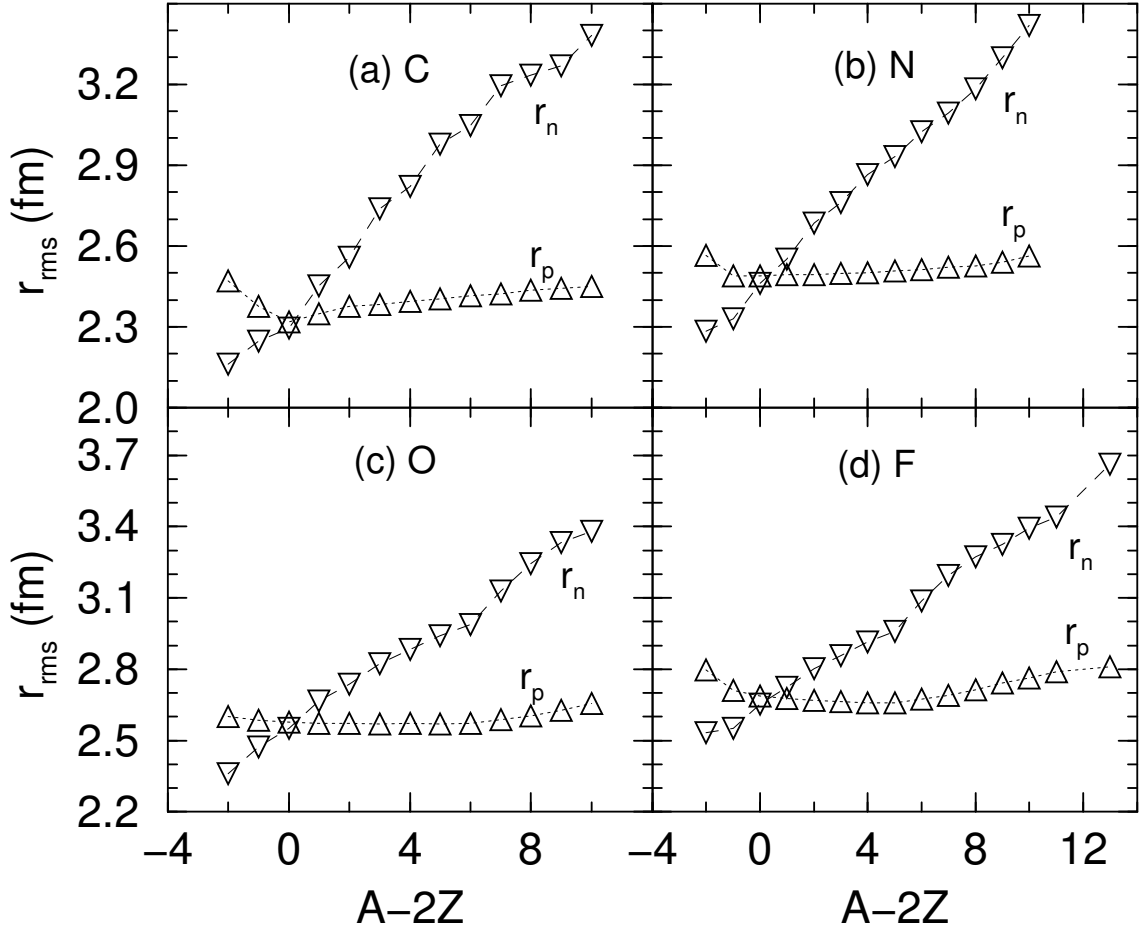


FIG. 3. The neutron and proton rms radii predicted by RCHB for the nuclei  $^{10-22}\text{C}$ ,  $^{12-24}\text{N}$ ,  $^{14-26}\text{O}$  and  $^{16-25}\text{F}$ .

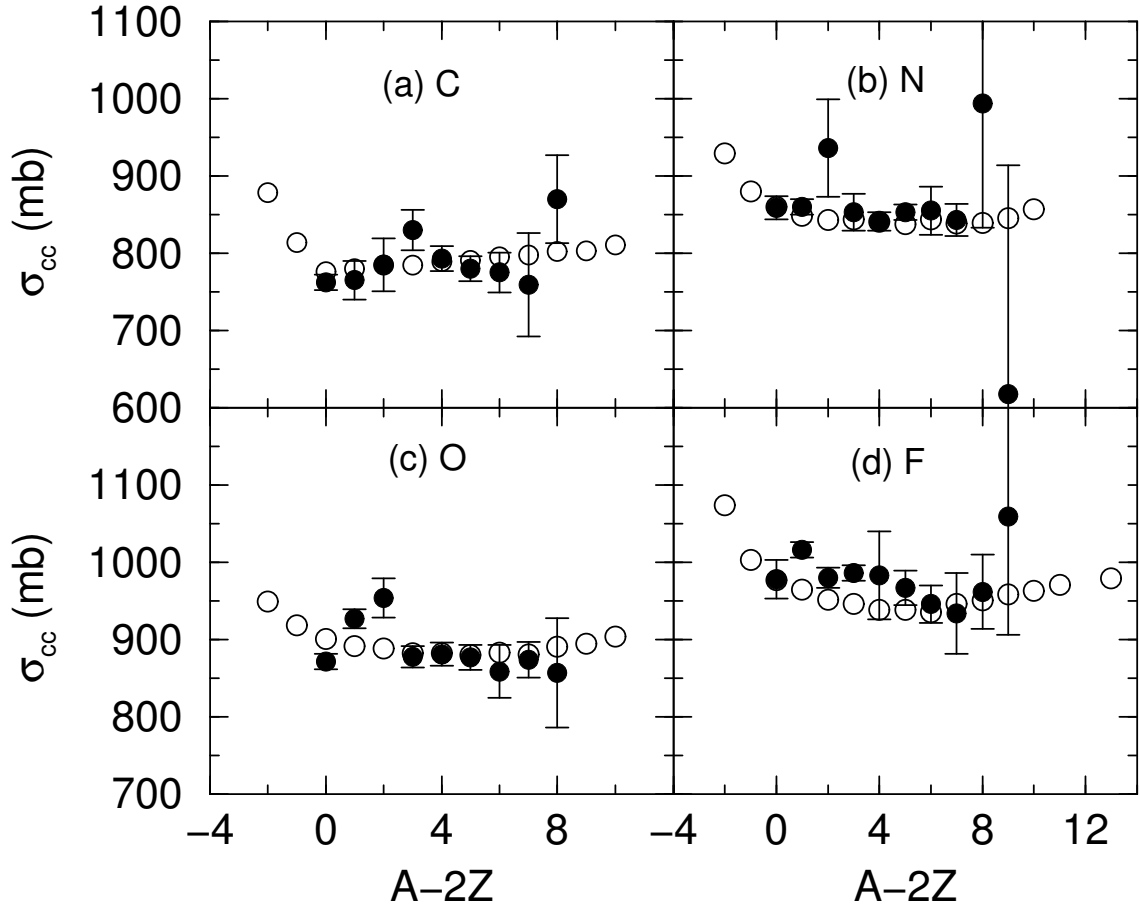


FIG. 4. The total charge-changing cross sections  $\sigma_{cc}$  of the nuclei  $^{10-22}\text{C}$ ,  $^{12-24}\text{N}$ ,  $^{14-26}\text{O}$  and  $^{16-25}\text{F}$  on a carbon target at relativistic energy. The open circles are the result of RCHB and the available experimental data are given by solid circles with their error-bars.